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(54) **Detecting harmonically-rich acoustic sources**

(57) A directional detector of a harmonically-rich acoustic source (e.g. a helicopter) comprises an array 11, 12 of microphones, preferably a two or three transducer array such as a Time-Average-Product Array, whose output signals are subjected (18) to 'cepstrum' analysis. This is a process in which the time domain array signals are transformed by Fourier analysis into the frequency domain and then the frequency spectrum is itself Fourier analysed, transforming the spectrum into the so-called "quefrency' domain in which the frequency related harmonic components of the original signal are additive and form one or more peaks characteristic of the identity of the source irrespective of the original signal being hidden by random background noise. Detection preferably includes source identification by comparison of 'cepstral' peaks with reference peaks of known sources. The array preferably includes means to steer the beam between different directions at which measurements are made.

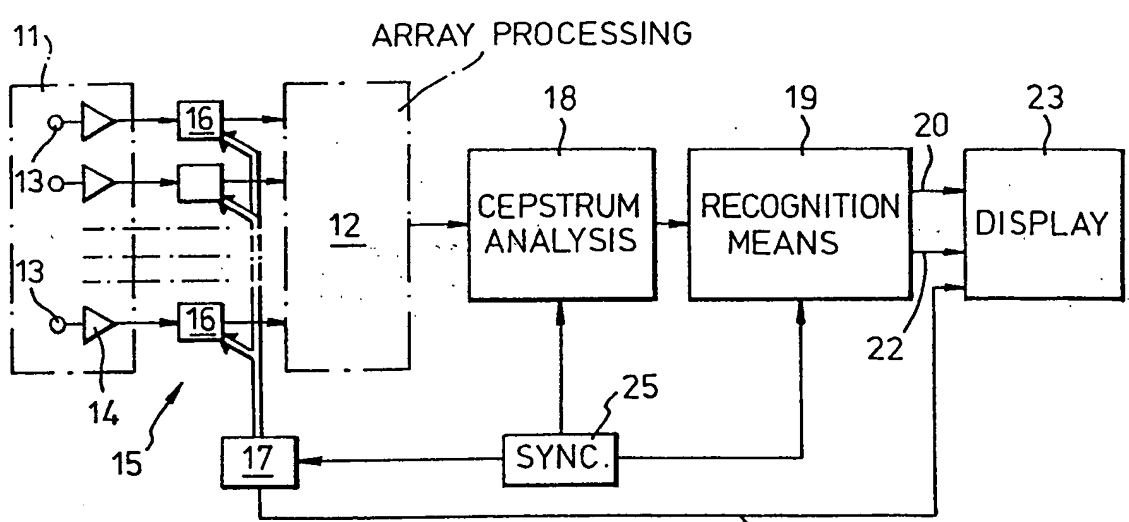

Fig.1.

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

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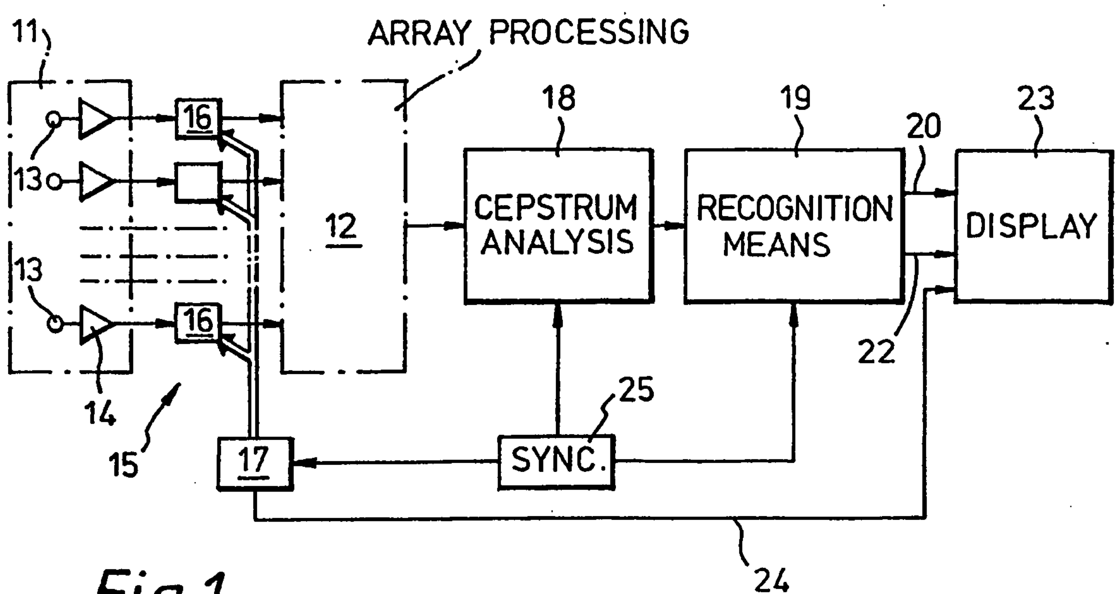
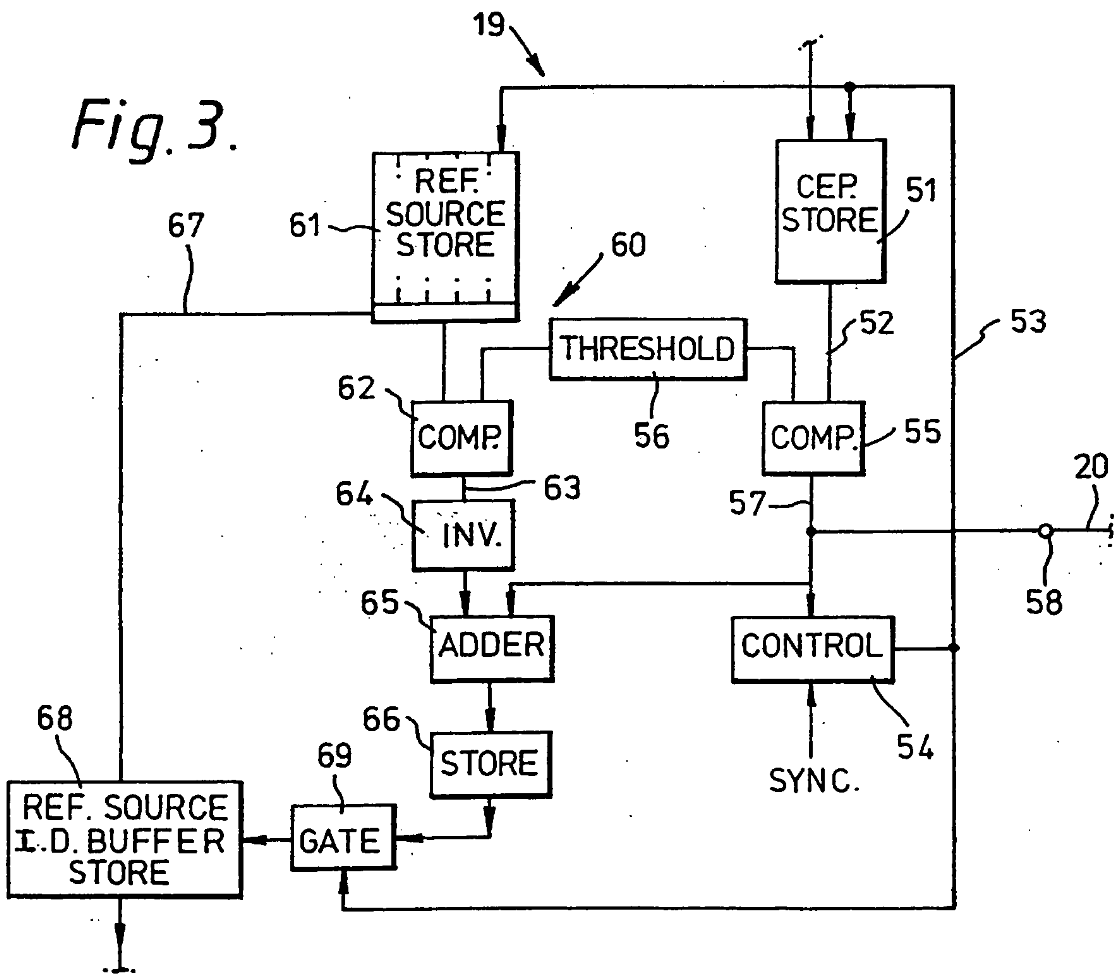

11
ARRAY PROCESSING
16
13
13
16
12
18
CEPSTRUM ANALYSIS
19
RECOGNITION MEANS
20
23
DISPLAY
22
14
15
25
17
SYNC.
24

Fig.1.

Fig.3.


19
REF. SOURCE STORE
61
67
60
CEP. STORE
51
52
53
THRESHOLD
56
62
COMP.
COMP.
55
63
64
INV.
57
20
58
65
ADDER
CONTROL
54
66
STORE
SYNC.
68
69
REF. SOURCE I.D. BUFFER STORE
GATE

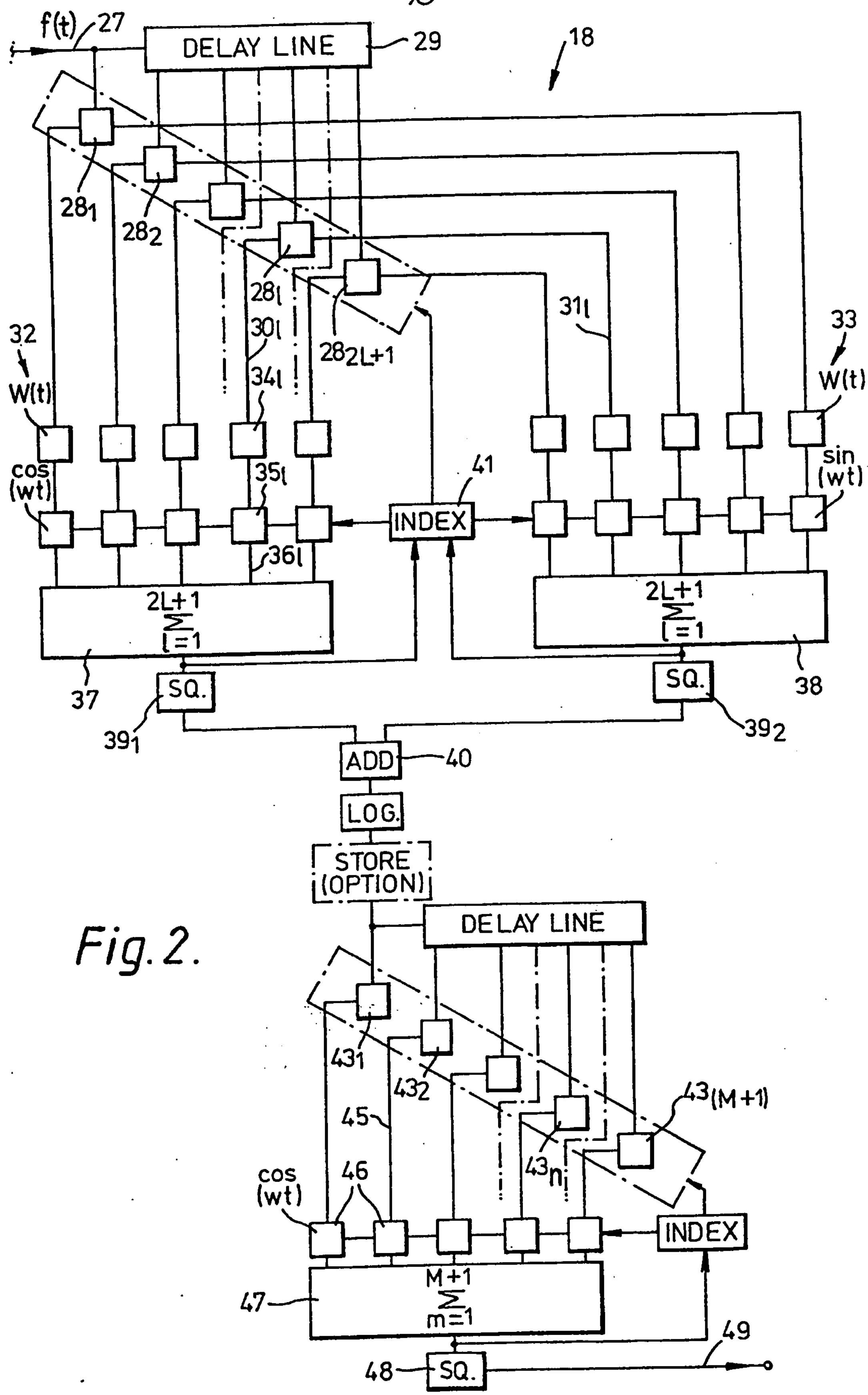

f(t)
27
DELAY LINE
29
18
28_1
28_2
28_l
28_{2L+1}
31_l
30_l
32
33
W(t)
W(t)
34_l
cos (wt)
35_l
41
sin (wt)
INDEX
36_l
2L+1 Σ l=1
2L+1 Σ l=1
37
38
SQ.
SQ.
39_1
39_2
ADD
40
LOG.
STORE (OPTION)
DELAY LINE
43_1
43_2
$43_{(M+1)}$
45
43_n
cos (wt)
46
INDEX
47
M+1 Σ m=1
49
48
SQ.

Fig. 2.

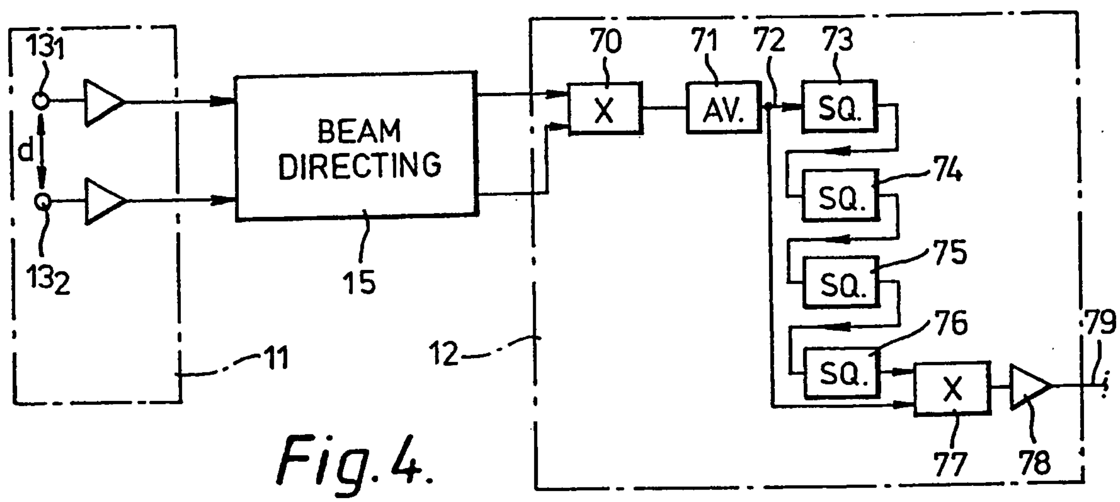

13₁
d
13₂
11
BEAM
DIRECTING
15
12
70
X
71
AV.
72
73
SQ.
74
SQ.
75
SQ.
76
SQ.
X
77
78
79

Fig. 4.

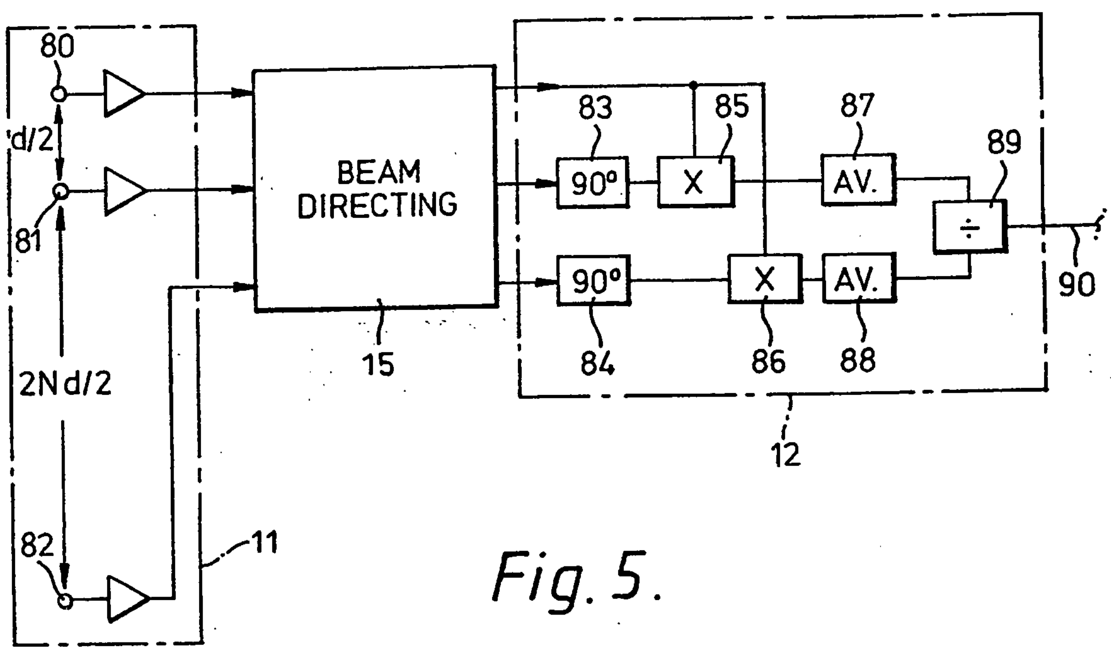

80
d/2
81
2N d/2
82
11
BEAM
DIRECTING
15
83
90°
85
X
87
AV.
89
÷
90
90°
84
X
86
AV.
88
12

Fig. 5.

SPECIFICATION

Detection of a harmonically rich acoustic source

This invention relates to the detection and directional location of a harmonically rich acoustic source and particularly of a fundamentally low frequency source such as a helicopter.

Helicopters are becoming used more offensively as gun-ships and operated at very low levels to avoid detection, such as hovering behind low hills or trees ready to spring to attack.

Traditional means of detection based upon high frequency electromagnetic radiation are ineffective when the helicopter is hidden by an obstacle.

It has long been recognised that low frequency acoustic emissions from such a craft, e.g. rotor blade noise, are not attenuated significantly by intervening obstacles but that identification of a source is difficult particularly a distant source when the acoustic signal is hidden in extraneous noises.

In many instances directional arrays of microphone transducers have been used to develop a directional reception beam which provides rejection of acoustic noise from other directions thereby aiding signal recognition in the beam direction which is steered enables the direction of a source to be identified also.

However to locate sources at low frequencies arrays containing a large number of transducers and in excess of 10m length may be required to combine an adequate signal to noise ratio and directivity while being effective only up to a few kilometres range.

Clearly an array of such dimensions is difficult to regard as a tactical device which is readily depolyed or redeployed frequently at different locations. Designs exist for arrays of small overall length composed of fewer transducers, which process the transducer signals to emulate the directional characteristics of the larger number of transducers. However the reduction in transducer numbers produces a corresponding reduction of background to noise rejection which has effectively restricted detection range for a tactical array.

One feature of low frequency sources such as helicopter rotors is that the emissions are rich in harmonics and it is an object of the present invention to provide a method of directionally detecting a harmonically rich acoustic source, and a directionally sensitive detector of a harmonically rich acoustic source, at greater ranges than has hitherto been possible.

It is also a further object of the present invention to provide a directionally sensitive detector of a harmonically rich acoustic source employing a smaller and simpler transducer array than heretofore.

According to one aspect of the present invention a method of directionally detecting a harmonically rich acoustic source comprises detecting acoustic emissions from a predetermined direction by means of an array of microphone transducers arranged to produce one or more directional reception beams and processing the signals received from the direction for one or more short time intervals by cepstrum analysis of the signals (as hereinafter defined) to determine the existance of any harmonically rich components of the signals.

The method may involve forming a single reception beam and include changing the direction of the beam reception for each time interval. The method may also include determination of the harmonic repetition period of harmonically rich acoustic emissions detected and/or recognition of a particular source by comparison of the harmonic reptition periods of the detected cepstrum signal and the cepstra of known sources.

According to a second aspect of the present invention a directionally sensitive detector of a harmonically rich acoustic source comprises an array of microphone transducers including processing means operable to process the mirophone signals so as to define a directional reception beam, beam directing means operable to define the direction of the reception beam in a region to derive signals representing sources at different directions with respect to the array location, cepstrum analysing means operable to derive a cepstrum (as herein defined) of the beam signal received from each direction and produce a cepstrum signal having a peak at a location in the quefrency domain indicative of the fundamental frequency of the acoustic emission of the source and recognition means operable to indicate detection of a cepstrum signal peak.

The logarithm of the amplitude spectrum of a periodic time signal with a rich harmonic structure is itself 'periodic' in frequency and analysis of the spectrum of the log amplitude spectrum reveals the harmonic repetition, or 'pitch' period of the periodic time signal.

A comprehensive discussion on cepstrum pitch determination is given in a paper of the same title by A. Michael Noll in the Journal of the Acoustical Society of America, Vol. 441, No. 2 1967, page 293. It is shown in that paper that for a periodic time signal f(t) whose Fourier transform is F(ω), the cosine and sine transforms of the log power spectrum are representable as $F_{cos}[\log|F(\omega)|^2]$ and $F_{sin}[\log|F(\omega)|^2]$, called the pseudo-autocovariance and pseudoquadrature autocovariance, respectively, from which the cepstrum C(τ) of a signal may be defined alternatively as the square of the pseudo autocovariance or the square of the pseudo-quadrature auto-covariance or, comprehensively, as the sum of the squares of the pseudo autocovariance and pseudo-quadrature-autocovariance, that is as

$$F_{cos}[\log|F(\omega)|^2]^2, \text{ or } F_{sin}[\log|F(\omega)|^2]^2, \text{ or as}$$

$$\{F_{cos}[\log|F(\omega)|^2]^2+F_{sin}[\log|F(\omega)|^2]^2\}$$

In this specification the term 'cepstrum' is used in accordance with these three interpretations of the definition but specifically, for purposes of description, with the first interpretation.

It will be appreciated from a study of the aformentioned paper that the function f(t) is initially transformed from the time domain F(ω) to the frequency domain and the power spectrum in the frequency domain is transformed to the so-called cepstrum in the so-called quefrency domain.

The directional array may be a conventional linear array employing a large number of microphone transducers, say between 15 and 20, spaced apart by approximately 1/2 the wavelength of interest. The main rotor of a helicopter, for instance, is likely to emit at a fundamental frequency of 20-30 Hz, that is, of wavelength λ = 10-15m, which would require a conventional array length of the order of 100m.

Such an arrangement is clearly unwieldy except for a permanent installation and it may be beneficial to tune the array to a harmonic of the fundamental frequency.

The amplitudes of low number harmonics are not significantly lower than the fundamental while beam directivity is increased and array length shortened by a factor of say two or four. However, such an array may still be of the order of 25m-50m long with elements to be deployed as accurately as possible every one to two metres.

Preferably, in accordance with the present invention, the array is composed of a small number of microphone transducers and the signals processed to emulate a larger number of microphone signals of an equivalent linear array composed of a larger number of microphone transducers. As stated above, such arrays and signal processing are able to eumulate the directivity characteristics of such equivalent linear arrays (E.L.A.) but because of the few transducers are subject to the effects of background e.g. wind, noise on the transducers. However in combination with the cepstrum analysis whereby harmonically rich emissions from sources of interest may be derived irrespective of noise level the use of such arrays in accordance with the present invention enables a detector to be constructed of small physical size and/or for ready tactical deployment and re-deployment.

The detector may be arranged with a plurality of beam directing means and cepstrum analysing means in order to define a plurality of differently directed beams simultaneously and to process the signals therefrom. Preferably, however the detector is arranged to define a single directional beam which is stepped through the region of inerest with cepstrum analysis being performed on the signals received whilst at each location.

Embodiments of the invention will now be described by way of example with reference to the accompanying drawings, in which:-

Figure 1 is a schematic representation in block form of a detector according to the analysing means of Figure 1,

Figure 2 is a block diagram showing in greater detail the cepstrum analysing means of Figure 1,

Figure 3 is a block diagram showing a greater detail the recognition mean of Figure 1,

Figure 4 is a block diagram showing one form of microphone transducer array suitable for use as the array means of Figure 1, and

Figure 5 is a block diagram of an alternative form of microphone transducer array for use in the detector of Figure 1.

Referring to Figure 1 directional receiving array of microphone transducers is shown by the two blocks 11, 12. The first block 11 comprises a transducer array consisting of plurality of spaced microphone transducers 13 each providing electrical signals in response to received acoustic signals by way of a pre-amplifier 14. The second block 12 comprises array processing means for the signals of the microphone transducers and may take any conventional form by which the signals are combined and/or weighted to produce a directional reception beam.

Detailed constructions of the receiving array are described hereinafter with reference to Figures 4 and 5.

Associated with the receiving array is beam directing means 15, comprising signal time delay elements 16 associated one each with the output of each preamplifier 14 by which the microphone signals are delayed by an amount determined for each element by beam directing control means 17. Essentially if a plane wavefront travelling at velocity c approaches the array at an angle ϕ to the line of the array, whose elements are separated by equal distances d, then the delay between the wavefront reaching successive microphones is $(d \sin \phi)/c$. It will be appreciated that c varies only by a small amount and may be considered a constant or be measured and the term d/c considered substantially constant during any operation so that the delays necessary between transducers can be readily calculated in control means, in order to direct the reception beam to be orthogonal to any wavefront approaching from any angle ϕ, and by varying the value of ϕ in discrete steps the receiving array can be caused to 'listen' at differing directions relative to the line of the array and thus scan a wide region while employing a narrow reception beamwidth. The beam directing means operates to step the beam through a plurality of directions in a 180° arc at intervals of the order of one second.

At each step of the scanned reception beam the signals received and processed in respect of that direction are applied to cepstrum means 18. The cepstrum analysing means 18 is described in greater detail hereinafter with reference to Figure 2 and operates on the signal received for each directional step of the beam which is a time varying function f(t) to provide the Fourier transform of the signal F(ω). The transform F(ω) contains real and imaginary terms which are squared and added to give a power spectrum $F(\omega)^2$ of which the logarithm is taken and a similar real part Fourier transformation performed on the $[\log F(\omega)^2]$ to derive the term $F_{cos}[\log F(\omega)^2]^2$ which is taken, according to the definitions hereinbefore, as equal to the

power cepstrum of the function f(t).

The signal produced by the cepstrum analysing means 18 is a function in the so-called quefrency domain, measured in units of time, and is fed to recognition means 19, described in detail with reference to Figure 2. The recognition means 19 scans the signal for a peak which includes an amplitude in excess of a predetermined threshold level, thereby providing a preliminary warning that the cepstrum analysis of the received acoustic signals has revealed a harmonically rich source and searches for the quefrency time of occurrences of said peak or peaks in order to identify, by comparison with the cepstrum responses of known sources, the source of the emission. In this example wherein enemy helicopters are to be detected, examples of cepstrum signals of the different types of helicopters employed are stored as reference cepstra with which comparison of the received cepstrum signal reveals its identify. The recognition signals produced by the recognition means 19 as supplied by lines 20, 21, 22 to a display facility 23, along with a signal on line 24 from the beam directing means 17 representing beam direction. The display means is organised in any convenient form to show that a harmonically rich source has been detected, recognised and the identity and direction of the source in relation to the array. The beam directing means 15, cepstrum analysing means 18 and recognition means 19 are all operated in synchronisation under the control of process synchronising means 25.

Referring now to Figure 2 which shows in detail the cepstrum analysing means its construction and function will be better understood by a brief consideration of the theory of cepstrum analysis given in the aforementioned paper by A.M. Noll. In summary thereof, the Fourier transform F(ω) of a time variable function f(t) is defined as:

$$F(\omega) = \int_{-oo}^{oo} f(t).e^{-j\omega t}.dt \qquad (1)$$

In practice it is impossible to integrate for an infinite time period and a multiplicative time window w(t) may be employed to time-limit f(t) such that $w(t) = 0$ for $|t| > T_w$. If the complex exponential is also separated into real and imaginary parts equation (1) becomes

$$F(\omega) = \int_{-T_2w}^{T_w} w(t).f(t).\cos(\omega t).dt - j\int_{-T_w}^{T_w} w(t).f(t).\sin(\omega t).dt \qquad (2)$$

The integration may be considered for solution by summation by application of Nyquist's theorem for sampling in the frequency domain, by which ω can be represented as $\omega = m.\Delta\omega$, where $\Delta\omega \leqslant 2\pi/2T_w$ and t can be represented as $t = 1.\Delta t$, where $\Delta t = 2\pi/2\omega_c$.

This equation (2) may be restated as:

$$\begin{aligned} F(m\Delta\omega) = \Delta t \sum_{1=-L}^{L} & w(1.\Delta t(.f(1.\Delta t)\cos(1.m.\Delta\omega\Delta t) \\ & - j\Delta t \sum_{1=-L}^{L} w(1\Delta t).f(1.\Delta t).\sin(1.m.\Delta\omega\Delta t) \end{aligned} \qquad (3)$$

where $1 = T_w/\Delta t$.

Thus F(mΔω) may be derived by taking 2L + 1 samples of f(t) at Δt intervals, performing the multiplication of terms for each value of 1 (= 1, 2..........L) and summing the results, both for the real and imaginary terms, squaring the sums, and adding them to produce them to produce one term, for a specific value m, of the power spectrum component $|F(m\Delta\omega)|^2$. Repeating this for each of a number of different values of m produces a series of special components which define the power spectrum $|F(\omega)|^2$.

Considering a similar treatment of the log power spectrum log $|F(\omega)|^2$, the power spectrum of which is defined as the cepstrum C(τ) then

$$C(\tau) = \{\int_{o}^{oo} \log|F(\omega)|^2 \cos(\omega\tau)\, d\omega\}\, 2 \qquad (4)$$

This may be considered for solution in a similar manner to the solution for the complex spectrum by Nyquist's sampling theorem which dictates that having samples the complex spectrum at $\Delta\omega \leqslant 2\pi/2T_w$ the

power spectrum must be samples at $\Delta\omega \leq 2\tau/4T_w$.
By taking $\tau = n.\Delta\tau$, where $\Delta\tau \leq 2\pi/\omega_c$,

$$C(n\Delta\tau) = \{ \sum_{m=0}^{M} \log | F(m\Delta\omega) |^2 \cos(m.\Delta.\omega.n.\Delta\tau \}^2 \quad (5)$$

where $M = \omega_c/\Delta\omega$, $n = 0, 1 \ldots\ldots N$ and N is an upper limit or desired quefrencies in the cepstrum. It will be appreciated that a similar sampling, term multiplication and summation will yield values for $F_{cos}[\log | F(\omega) |^2]$ which when squared provides one form of the cepstrum of the function, that is, the square of the cosine transform of the log power spectrum,

$$C(\tau) = \{F_{cos}[\log | F(\omega) |^2]\}^2 \quad (6)$$

In the cepstrum analysing means 18 shown in Figure 2 the time varying signal produced by the receiving array processing means 12 extends for the time that the beam is at a particular step, say, 1 second, and is applied on line 27 to a sample-and-hold circuit 28_1, and by way of a tapped delay line 29 to 2L other sample-and-hold circuits 28_2, 28_3 ....28_{2L+1}. The delay property of the delay line 29 is a function of the 1 second step time interval which defines the duration of the time window $-T_w$ to $+T_w$ and has tappings spaced to represent regular intervals Δt.

Each sample and hold circuit 28_1 has two outputs 30_1 and 31_1 which provide signals to the real-part and imaginary part multiplication regions 32 and 33 respectively. Considering multiplication region 32 the input 30_1 feeds a sample of the input signal to a first, or time window, multiplying element 34_1 which performs the multiplication $w(1.\Delta t)$ and then to second, or cosine, multiplying circuit 35_1 where it is multiplied by the particular value assigned to $\cos(1.m.\Delta\omega\Delta t)$. The final product, $f(t.)w(t).\cos(1.m.\Delta\omega\Delta t)$ is applied by line 36_1 to addition means 37 wherein it is summed with the equivalent product of the other 2L multiplication paths. The corresponding imaginary-part multiplication region 33 has addition means 28. The output of addition means 37 and 38 represent $F_{cos}(m.\Delta\omega)$ and $F_{sin}(m.\Delta\omega)$ respectively and are fed to squaring circuits 39_1, and 39_2, respectively and then to addition means 40 which produces the power spectrum $|F(m.\Delta\omega)|^2$ of the input function. This procedure is repeated m times for different samples of the input function by means of indexing circuit 41 which causes the value of m to be indexed and the sample and hold circuits 28 to re-apply the samples to the multiplying region 32.

The output of the addition circuit 40 is fed to a logarithmic circuit 42 which produces a signal representing the logarithm of the power spectrum component and the components are stored in a store such as shown ghosted at 42' or is applied both to sample-and-hold circuit 43_1, and by way of delay line 44 taps to sample and hold circuits 43_2.... $43_{(M+1)}$. The sample and hold circuits have outputs 45 providing signals to M + 1 cosine multipliers 46 in which the log power spectrum components $\log|F(m\Delta\omega)|^2$ for each value of m are multiplied by the appropriate value of $\cos(m.\Delta\omega.n.\Delta\tau)$ and the products summated in addition means 47 to provide an output representing $F_{cos}[\log | F(\omega)|^2]$. This cosine of the log power spectrum of the signal f(t) is squared in squaring circuit 48 and fed to cepstrum analysing means output terminal 49 as $C(n.\Delta\tau)$ of equation (5). The second transformation is repeated for different values of n in the cosine multiplier by indexing means 50 which operates in a similar manner to that 41.

The cepstrum signal derived from terminal 49 comprises a series of N values of $C(n.\Delta\tau)$ which form a signal extending in the quefrency domain which is measured in units of time. That is, if the original time domain function signal f(t) contains emissions rich in harmonics, from a source then the regularity caused by such haromics in the frequency domain function will result in a signal peak at some point in the quefrency domain determined by the original frequency separation of the harmonics, that is, the fundamental frequency.

It will be appreciated that in accordance with the definitions given of the cepstrum the arrangement of Figure 2 may be operated with the cosine multiplying circuits 46 replaced by sine, multiplying circuits or with additional sine multiplication, addition and squaring means (not shown) corresponding to the region 33, 38, 39_2.

It will be appreciated that the portion of the circuit prior to the squaring means 39 is a conventional spectrum analyser for which may be employed one of the many types available commercially.

Similarly it will be appreciated that the transformation means from delay line 44 to addition means 47 may also employ a spectrum analyser, the analysers being coupled by way of squaring and addition means 39 logarithm generator 42 and an intermediate store 42' for the m component samples of the frequency spectrum applied to the second analyser, and producing an output by way of squaring circuit 48.

In the cepstrum analysing means described with reference to Figure 2 or one employing spectrum analysers as outlined above, the second transformation is only able to be made when the component samples resulting of the first are available. It will be appreciated that where the complex function analyser is not employed immediately in the transformation of another function is may be employed, by suitable

alteration of the multiplying factors, to perform the power spectrum transformation.

Referring to Figure 3 which shows the recognition means in greater detail, the cepstrum signal produced by the cepstrum analysing means is applied to a store 51. The store is arranged to reproduce the stored cepstrum signal as a series of N sample quefrency values on output line 52 under the control of read instruction received on line 53 from control means 54.

The line 52 is connected to a level comparator 55, with a determined threshold level from a source 56 such that if any sample of the cepstrum signal read from the store has a value in excess of the threshold level a detection signal is given on line 57 to terminal 58, indicative of the detection in the original signal of a harmonically rich source.

The line 57 is also connected to the control means 54 to initiate recognition of the source as the result of this preliminary detection.

The source recognition portion, shown generally at 60 comprises a reference source 61 containing details of the cepstral peaks of known reference sources i.e. helicopter rotors. For each reference source the store contains a block of N+1 sample locations one or more of which store values large enough to represent a cepstral peak. The block also contains the identity of the source.

The store is arranged such that the blocks are accessed in turn by the control mean 54 and the samples read out in synchronisation with the samples from the cepstrum store 51. The output of the reference store is connected to a comparator 62 to which the threshold device 56 is also connected to produce a signal at line 63 when a cepstral level in excess of the threshold is produced by the reference cepstrum. The line 63 is passed by way of an inverter 64 to one input of a binary adder 65 to which the output 57 of comparator 55 is also applied. The output of the adder is fed to a store 66.

The reference store 61 has a second output 67 on which the reference source identity is developed for the source under comparison and applied to a source identity buffer store 68. The output of the buffer store is connected by a gate 69, controlled by store 66, to the line 22. The adder 65 thus produces a '1' output whenever there is identity between the comparator signals, including identically located cepstral peaks, but produces a '0' output when there is a discrepancy between the locations of cepstral peaks. The adder output is applied to store 66 which opens gate 70 to the passage of source identity from buffer 69 if the comparison has been completed for the N sample steps with no '0' output i.e. no disagreement on cepstral peaks.

It will be appreciated that this circuit is exemplary only of many forms of detection circuit which may be employed all of which are open to small modifications. For instance in the circuit of Figure 3 the store 66 may be omitted and a '0' output of adder 65 fed to the control means 54 to interrupt the comparison and index to the next reference source, the gating signal being supplied by the control means 54 automatically if it completes a comparison uninterrupted by a signal from adder 65.

The method of storing the reference date is also open to a choice depending upon the storage arrangements used. For instance instead of the use of blocks of storage for each reference store, for which most sample locations will be zero, the storage means may store the peak forms and their relationship relative to the samples numbers at which they are to be retrieved.

Thus once a cepstrum signal has been detected as exceeding the threshold set by comparator 55, the signal is examined in respect of peaks occurring at quefrencies corresponding to those of known reference sources for a plurality of reference sources in rapid succession until identification is made. Alternatively (not shown) the output detector may be arranged to control a counter of clock pulses by which the count related to peak detection(s) may form a quantitive measure of quefrency time enabling reference to be made manually to reference data.

The display unit 23 may take any convenient conventional form being a visual display e.g. of illuminated indicia or alphanumerically or graphically generated information or an audible tone or combination of both. The display unit 23 as mentioned earlier receives reception beam angle information from the beam directing means 15 which it displays also, for example, either only in response to a detection or permanently as a check of beam scanning and highlighted or otherwise changed upon detection.

The display unit may also communicate with the beam directing means 15 to cause the beam scanning pattern to be broken and the beam locked onto the direction of a detected source.

The beam direction scanning steps of the cepstrum analysis and source recognition all require operations to be formed on segments of a continuing signal and it will be appreciated that synchronisation means 25 controls passage of the signals through the various stages at the appropriate times.

The detector so far described is suitable for use with many types of microphone array providing the directional reception beam. Both linear arrays, which may have size disadvantages as outlined above, and arrays of small members of microphone transducers in which the microphone signals are processed in order to produce a reception beam having a reception beam characteristic corresponding to an equivalent linear array (E.L.A) of a greater number of transducers.

Examples of such arrays are to be given in the papers "Theory of Time-Averaged-Product Arrays" by A. Berman and C.S. Clay in the Journal of the Acoustical Society of America, Volume 29, No. 7, 1957, page 805 and "Design of Directional Arrays" by J. L. Brown and R. O. Rowlands in the Journal of the Acoustical Society of America, Volume 39, No. 12, 1959, page 1638.

In general such arrays with their signal processing achieve the beamwidth characteristics of larger E.L.A.'s at the expense of the smaller number of microphone signals from which the reception beams signal is produced having an inferior signal-to-background noise ratio which for conventional distant detection

purposes limits the usefulness.

It will be appreciated that in the detection arrangement of the present invention the use of cepstrum analysis to derive and identify harmonic signals from a high level of random background noise enables such arrays to be used with great effect.

Array configurations in which the physical dimensions of the array are small, or the numbers of transducers small enough to handle easily, are particularly useful to the presently considered example of helicopter detection under battle conditions. Arrays containing small numbers of microphone transducers, say two or three, may be carried by a vehicle for rapid deployment and examples of such arrays will be given for completeness.

Considering a linear array of 2Q transducers and the reference point the centre of the array the normalised sum pattern for the array has the form

$$P_{2Q}(\phi) = \sum_{K=1}^{Q} B_K.\cos[(2K-1).(\pi d/\lambda).\sin\phi)] \qquad (7)$$

where d is the transducer spacing, λ the wavelength of the incident signal, ϕ the angle between the incident wavefront and array axis, and B_K is a weighting coefficient. The expression (4) may be simplified to

$$P_{2Q}(\phi) = \sum_{K=1}^{Q} B_K.\cos[(2K-1)U \qquad (8)$$

where $U = (\pi d/\lambda)\sin\phi$.

It will be seen that the output from the first tranducer is proportional to cos U and that from the K^{th} tranducer proportional to cos (2K − 1) U so that the output for the K^{th} transducer may be generated from that of the first using the recursion formula:-

$$\cos KU - 2\cos U.\cos(K-1)U - \cos(K-2)U$$

By considering cos U = Z and an E.L.A. of 18 transducers, (that is K = 1, 2, ...9) the equation (8) expands to

$$P_{18}(\phi) = \cos U + \cos 3U + \cos 5U + \cos 7U + \cos 9U + \cos 11U + \cos 13U + \cos 15U + \cos 17U, \text{ and}$$

$$P_{18}(\phi) = 6553Z^{17} - 262144Z^{15} + 430080z^{13} - 37276Z^{11} + 183949Z^{9} - 50688Z^{7} + 7392Z^{5} - 480Z^{3} + .9Z$$

for unitary shading of the transducers of the linear array. If Binomial shading is applied to the terms of this series, using values derived from the Pascal triangle, the sum pattern changes to $P_{18}(\phi) = 24310\cos U + 19448\cos 3U + 12376\cos 5U + 6188\cos 7U + 2380\cos 9U + 680\cos 11U + 136\cos 13U + 17\cos 15U + \cos 17U$

Employing the recursion formula to expand the series gives the result:-

$$P_{18}(\phi) = 65536\,Z^{17} \qquad (9)$$

and it will be seen from the parameters shown of a class III T-A-P array given by Berman and Clay that the product of the signals from spaced transducers multiplied and averaged is Z. Referring now to Figure 4 which shows such an array and processing configuration for generating the response, equation (9), of an E.L.A. of 18 transducers.

The two microphone transducers 13_1 and 13_2 are located distance d apart, where d is substantially $\lambda/2$ of the wavelength of interest. The signals after passing through the beam directing means 15 are multiplied together by multiplier 70 and averaged by averaging circuit 71 to produce a signal representing the value Z at 72. The signal is passed through squaring circuits 73-76 connected in tandem to generate the sixteenth power of Z and then multiplied by the original signal Z from 72 in second multiplier mean 77. The signal is then amplified by amplifier 78 to effect multiplication by the constant of equation (9) and produced at output terminal 79 for transmission to the cepstrum analysing means 19 (Figure 1)

It will be appreciated that while an array of two elements can be used to emulate a larger E.L.A. the practical difficulties of achieving this in the general unitary shading case, for example by solving equation (8) demonstrate the practical advantages of considering the emulation of a binomially shaded E.L.A.

However in practice binomial shading while producing rejection of side lobes to the main reception beam does result in a beamwidth which may be unacceptably wide compared with the use of the normalised unitary shading or pattern.

Considering now the case of a (2Q + 1) transducer E.L.A. the normalised pattern has the form:-

$$P_{2Q+1}(\phi) = \sum_{K=1}^{Q} \cos 2KU \qquad (10)$$

when $U = (\pi d/\lambda).\sin\phi$ as before. It may be shown

$$\sum_{K=1}^{Q} \cos 2KU = 1/2 + [\sin(2Q+1)U]/2.\sin U$$

so that

$$P_{2Q+1}(\phi) = 1/2 + [\sin(2Q+1)U]/2.\sin U \qquad (11)$$

Referring now to Figure 5 which shows a directional receiving array based upon the above equation (8) the array portion 11 employs three microphone transducers, a first or datum microphone 80, a second microphone 81 spaced from the first by a distance d/2 (where d is the separation of transducers in an E.L.A.) or $\lambda/4$ of the wavelength of interest and a third 82 spaced from the first by a distance $(2Q + 1)d/2$. Signals from the microphones are fed by way of the beam directing means 15 to the array processing means 12. The inputs from microphones 81 and 82 are fed by way of 90° phase shifters 83, 84 respectively to multiplicaton circuits 85, 86 respectively where each is multiplied by the input signal from microphone 80. The products of the multiplications are averaged in averaging circuits 87, 88 respectively and applied to a division circuit 90.

Assuming the signal from datum microphone 80 to be $\sin(\omega t)$ the phase shifted second microphone signal to be $\cos\omega(t - (d/2c)\sin\phi)$ the averaged product,

$$P_{av} = 1/2.\sin[(\pi d/\lambda).\sin\phi], \text{ which is equal to}$$

$$P_{av} = 1/2.\sin U \qquad (12)$$

Similarly the phase shifted signal from microphone 82 is $\cos\omega(t - [(2Q+1).d/2c]\sin\phi)$ and the average of the product with the signal from the datum microphone is

$$1/2.\sin(2Q+1)U \qquad (13)$$

The divisions of the signal representing equation (13) by that representing equation (12) produces at output terminal 90 the signal equivalent of equation (11), (with the exception of the constant).

This form of array thus emulates an equivalent linear array using unity shading resulting in a narrower beamwidth of the main lobe but less rejection of side lobes than the two element array described above. Also it will be appreciated that the array is not as compact as the two element array in requiring the third element to be displaced a distance $(2Q + 1)\,d/2$ from the datum but the overall array length is substantially half that of an equivalent linear array and as only a single transducer has to be deployed and redeployed relative to the first and second which may be vehicle mounted this may be achieved relatively easily under battlefield conditions.

In any of the above described transducer arrays the total number of transducers used or emulated is open to choice by appropriate choice of value for Q applied in solving the equations shown. In particular in the two element solution it can be shown that for any 2Q transducer array equation (9) is a function of $Z^{(2Q-1)}$.

It will be appreciated that the above described microphone transducer arrays represent examples only of such configurations which may be designed utilising the criteria presented in the papers referred to.

For clarity the above description has referred to a single linear array and alternatives therefor in which it is assumed a single directional beam is produced. As such linear arrays would tend to form a second main lobe at 180° to the first such a 'backward' lobe may be suppressed by any known technique such as screening the microphone transducers from rearward reception or by forming a second array orthogonal to the first and operated in an 'end-fire' mode to limit reception in the main array, operated in a 'cross-fire' mode, by multiplication of the signals to the forward facing lobe only.

Thus the use of cepstrum analysis of acoustic inputs permits the determination of harmonically rich sources such as helicopters at distances wherein their time domain signals are lost in background noise, thereby enabling detection at greater distances than with conventional multi-transducer arrays and the use in battlefield conditions of physically compact two-and-three transducer arrays within their relatively poor

transducer signal-to-noise response.

The above described arrays have accorded with general practice in having the dimensions, that is, transducer separation, tuned in relation to the wavelength of interest. It will be appreciated that an object such as a helicopter may comprise sources at different fundamental frequencies e.g. a main rotor at about 25Hz and tail rotor at about 100Hz. It will be appreciated that if the two sources are to be employed to identify the object it is not feasible to tune a single array to both fundamental frequencies but it is feasible to tune the array to within the fundamental frequency range of the tail rotor and also a harmonic of the main rotor.

The separations of transducers given above are in relation to the conventional separations in linear arrays of $\lambda/2$, where λ is the wavelength of interest. It can be shown by by tolerating a small increase in aliasing lobes the main lobe beamwidth can be decreased to form a narrower beam width with transducer separations in a range between 0.5λ and 0.75λ. Where it is desired to detect several frequencies within a range the array is preferably 'tuned' such that the array transducer separations lie between these values of λ.

The use of an array tune to a low harmonic of a source may be beneficial in other ways. For instance at the low fundamental frequencies contemplated for helicopter rotor detection wind noise may produce such large signal amplitudes that the processing circuitry becomes limited. The input preamplifiers 14 connected to the microphone transducers may include filters to eliminate such signals even when they include the source fundamental, the ratio of harmonics providing all the information required.

The above description has related specifically to the production of a single directional reception beam which is stepped through a region to provide signals for the cepstrum analysis. In a practical embodiment at the frequencies of about 100 Hz a reception beamwidth of about 10° may be obtained by the few-transducer arrays described. Thus by stepping through 18 positions at 10° intervals at say 1 step per second a region of 180° may be examined every 18 seconds. It will be appreciated that if the beam forming and cepstrum analysing means is duplicated any number of beams may be formed simultaneously in any direction from the array, giving a more frequent scan or 'instant' information of detection in all directions by simultaneous non-scanning beams. The cepstrum analysis would then be performed for discrete, consecutive or overlapping time intervals in accordance with common spectrum analysis practice.

It will be appreciated that the processing circuitry employed in the array processing means 12, cepstrum analysing means 18, recognition means 19 and in the beam directing means 15 may be either analogue or digital in nature and in the latter case may be implemented by one or more microprocessor devices having fixed in the storage media thereof the instruction sequences necessary to operate upon the signals produced by the transducers to perform the detection described above.

CLAIMS

1. A method of directionally detecting a harmonically rich acoustic source comprising detecting acoustic emissions from a predetermined direction by means of an array of microphone transducers arranged to produce one or more directional reception beams and processing the signals received from the direction for or more short time intervals by cepstrum analysis of the signals (as herein defined) to determine the existence of any harmonically rich components of the signals.

2. A method as claimed in claim 1 in which a single reception beam is formed including changing the direction of the beam reception for each time interval.

3. A method as claimed in claim 1 or claim 2 including determination of the harmonic repetition period of the harmonically rich acoustic emissions detected.

4. A method as claimed in claim 3 including comparing the haromic repetition period from the cepstrum of a detected source with harmonic repetition periods derived from the cepstra of known sources.

5. A method of directionally detecting a harmonically rich acoustic source substantially as herein described with reference to and as shown in the accompanying drawings.

6. A directionally sensitive detector of a haromically rich acoustic source comprising an array of microphone transducers including processing means operable to process the microphone signals so as to define a directional reception beam, beam directing means operable to define the direction of the reception beam in a region to derive signals representing sources at different directions with respect to the array location, cepstrum analysing means operable to derive a cepstrum (as herein defined) of the beam signal received from each direction and produce a cepstrum signal having a peak at a location in the quefrency domain indicative of the fundamental frequency of the acoustic emission of the source and recognition means operable to indicate detection of a cepstrum signal peak.

7. A detector as claimed in claim 6 in which the array is arranged to be operated when stationary and produce a single reception beam whose direction is determined by signal delay means associated with each microphone transducer operable to delay the signals produced by each microphone as a function of the delay in incidence of the acoustic wavefront on the microphone transducers at different angles to the line of the array.

8. A detector as claimed in claim 6 or claim 7 in which the microphone transducers are arranged in a time-average-product (T-A-P) array comprising a small number of microphone transducers and array processing means operable to produce for the array signal characteristics of the reception beamwidth of an equivalent linear array composed of a larger number of transducers.

9. A detector is claimed in claim 8 in which the array is a class III T-A-P array employing two microphone

transducers spaced apart by an amount between 0.5 and 0.75 of the wavelength of interest.

10. A detector as claimed in claim 9 in which the array emulates an equivalent linear array having an even number 2Q of equally spaced transducers and in which the array processing means is arranged to process the signals in accordance with a binomial shading pattern applied to the transducers of the equivalent linear array.

11. A detector as claimed in claim 10 in which the array processing means comprises means to determine the product of the signals from the two microphone transducers, the time average of the product signals and the $(2Q\text{-}1^{th})^4$ power of said average signal.

12. A detector as claimed in claim 6 or claim 7 in which the array emulates an equivalent linear array of an odd number (2Q+1) of transducers comprising three microphone transducers one of which represents a datum transducer from which is spaced a second transducer by a distance substantially one quarter of the wavelength of interest and a third transducer spaced from the datum transducer by (2Q+1) times the distance between the datum and second transducers, and array processing means comprising phase shifting means operable to phase-shift the signals from the second and third transducers by 90°, multiplication means operable to multiply each of the phase shifted signals by the signal from the datum transducer, means to average the signals representing the multiplication products and division means operable to provide signals representative of the ratio of the signals derived from the datum and third transducers and from the datum and second transducers.

13. A detector as claimed in any one of claims 6 to 12 including high pass filter means associated with each of the microphone transducers operable to block signals below the cut off frequency of the filter due to wind noise.

14. A detector as claimed in any one of claims 6 to 13 in which the cepstrum analysing means compress first transform means operable to form the Fourier transform of a signal received from the array within a said short time interval in terms of its real and imaginary transform parts, means operable to square the signals representing each of the transform parts and add them to generate signal representing the power spectrum, means operable to generate the logarithm of the power spectrum, second transform means operable to form at least one of the real (cosine) or imaginary (sine) Fourier transforms of the log-power spectrum, and means operable to form the square of each output of the second transform means and the sum of more than one such squares.

15. A detector as claimed in any one of claims 6 to 14 in which the recognition means comprises signal level detection means responsive to a cepstrum signal peak in excess of a preset amplitude to determine from the cepstrum quefrencies at which the peak is detected the harmonic ratio period of the original time function.

16. A detector as claimed in claim 15 in which the recognition means includes storage means operable to store the cepstrum time intervals associated with significant peaks of at least one known source as a reference and comparison means operable to determine substantial agreement between the cepstrum quefrencies of generated cepstral peaks and stored reference peaks to produce an output indicative of the detection of a particular source.

17. A directionally sensitive detector of a harmonically rich acoustic source substantially as herein described with reference to, and as shown in Figures 1 to 3 and Figure 4 or Figure 5 of the accompanying drawings.

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